



EXP-20

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ACCELERATOR EXPERIMENT--High-Field Equilibrium Orbit in the Main Ring

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This report summarizes the results of measuring the high-field equilibrium orbit and discusses the correction of orbit distortions by transverse displacement of the quadrupoles. It is a sequel to EXP-10 (5/30/72). An effort is made to evaluate the success of our past efforts as a guide for further orbit corrections.

I. Chronology of Measurements and Moves

Table I records all of the complete equilibrium-orbit measurements. Those of 4/12, 4/14, 5/28 and 7/9 were the most carefully verified and make up the useful data base, although the other measurements were useful in checking the effects of immediately prior moves. Table II is a record of quadrupole moves taken to correct the closed orbit. The predicted rms and maximum orbit distortions are compared with those measured before and after the moves. One finds that the moves have always smoothed the orbit but only on the first attempt was the result as good as predicted. However, there is some evidence that the amount of discrepancy is dependent on the interval between the "before" and "after" measurements. Sources of the discrepancies are discussed below.

II. Precision of Closed-Orbit Measurements

With present beam intensities and the condition of the detectors and their cables it has been estimated (R. Stiening) that position measurements are no better than $\pm 1/16''$ ($\pm .5$ db in raw data). This approaches the order of the current vertical rms distortion and is adequate to account for the difference between the $.09''$ rms vertical predicted after the moves of 5/2 and the $.15''$ observed 5/28. The horizontal discrepancy is similar. Clearly, current orbit measurements contain significant noise. The tolerable S/N ratio depends on how detailed a fit is going to be made. To calculate the move of one quad only the correct sign is needed for most detectors, and information with S/N approaching unity is of some use. Probably S/N should be $\sim \sqrt{n}$ for an n quad move to make much improvement.

III. Quadrupole Placement Accuracy

A further limitation on the making of refined corrections is the practical difficulty in achieving an exact set of moves. The actual error in measuring the change of quadrupole position is quite small ($.001''$) since dial gauges remain in contact with the magnet during the move. There are practical difficulties in obtaining the requested setting, however. Limits on jack travel often interfere; coupling to upstream and downstream bending magnets may require compensating bending magnet moves. Also, one must avoid disturbing positions in the direction orthogonal to the intended move. Each move thereby requires several iterations and one must quit after some reasonable length of time. A comparison between the vertical moves requested

and those the moving crew were able to deliver on 5/2 is given below.

<u>Quad</u>	<u>Requested Motion (in)</u>	<u>Obtained (in)</u>	<u>Diff (in)</u>
A18	-.057	-.043	-.014*
A43	-.017	-.016	.001
D23	-.086	-.077	-.011*
D47	+.048	+.047	.001
F43	-.036	-.036	.000
F45	-.050	-.050	.000

These motions lead to the following predictions for the closed-orbit distortion:

	<u>From Requested Moves</u>	<u>From Actual Moves</u>
Predicted rms	.087"	.090"
Predicted Max	.225"	.238"

Thus, for this particular case the moves actually made should have been nearly as good as those requested. In general, however, a single placement error of .01" produces an rms orbit error of .015" and a maximum discrepancy of .025". Thus, in an n magnet move one would expect the rms error after correction to be

$$\epsilon = \sqrt{n(1.5\delta)^2 + \epsilon_0^2}.$$

where ϵ_0 is the predicted rms error, δ is the typical placement error, and the numerical factor 1.5 is the ratio between the transverse

* limited jack travel

displacement of a 7' focusing quad and the rms orbit distortion produced thereby. One must expect greater error in the predicted maximum because the errors do not add in quadrature and because the numerical factor is 2.5 instead of 1.5. For the horizontal moves of 5/12 a similarly detailed table of actual moves has not been made up, but E. Bleser summarizes the results by saying that all moves are within $\sim .005$ " of target and that for the techniques used on that date the measurement error is also of that order. Thus, placement error is not likely to be a significant contributor to the discrepancies observed between measured and predicted closed orbits.

IV. Unexpected Changes

Although it has been argued that the apparent improvement in rms and maximum distortion shown by the measurements of 5/28 was reasonable in view of uncertainty in the 5/14 measurement, the agreement in detail was much worse than that obtained in the trial case formed by the measurements of 4/12 and 4/14 and the vertical moves of 4/13. When the data of 5/7 are used, however, the point by point comparison is considerably improved even though the quality of that earlier data is believed to be inferior to that taken on 5/28 (see Fig. 1). Of course, the horizontal moves of 5/12 have taken place in the meantime, but it appears that something else significant has occurred in the interval 5/7 to 5/28. The shorted 4' defocusing quad found at All on 6/27 may have become defective during this period. This effect is clearly present in a comparison of the data of 5/28 with that taken 7/9 after the All quad had been replaced.

Figures 2 and 3 give the difference between the two measurements showing in both planes the sinusoidal form characteristic of a simple source. The orbit correction program applied to these differences selects AllD and moves it in the direction consistent with the fact that the upper outside coil was shorted. The effect of moving All was

	<u>Before</u>		<u>After</u>	
	<u>rms</u>	<u>max</u>	<u>rms</u>	<u>max</u>
Vertical orbit difference	.142	.30	.079	.365
Horizontal orbit difference	.413	1.10	.195	1.027

As one can see from the figures and the tabulation, the movement of All made a large rms reduction in the orbit distortion but failed to improve the value of the maximum distortion. These large localized distortions in the corrected difference orbit are suggestive of local measurement errors in one or the other sets of data because the match is so good over most of the ring. Caution is in order in interpreting the difference orbit, however, because both sets of data are noisy. The correction subtracts out a sinusoidal component and leaves a yet noisier second difference which may be expected to show large fluctuations. The precision of these data does not justify a strong statement about failure of specific detectors.

V. Program for Further Improvements

The current closed orbit shown in Figures 4 and 5 is clearly in need of further improvement. For the horizontal orbit the rms distortion is still well above the noise, the ratio 2.72 of maximum to

rms is in the normal range, and areas in need of correction are well distributed around the ring. Therefore, an overall correction is indicated. Five moves chosen to minimize the rms error are given below.

<u>Quad</u>	<u>Move</u>	
A15	.114"	inward
A32	.085"	} outward
B16	.082"	
D43	.062"	
F23	.132"	
Predicted rms	.180"	
Predicted max	.547"	at EllF

The resulting max-to-rms ratio is somewhat high reflecting a kink developed at Ell, but it is reasonable to see if the kink actually shows up in the measurements before trying to correct it. The corrected orbit is the dashed curve in Fig. 4.

The vertical closed orbit looks a bit different. About 2/3 of the sensor readings are around the noise level and the max-to-rms ratio definitely reflects localized distortion. The moves suggested below are chosen to reduce the distortions in E and F sectors with little effect on the rest of the machine.

<u>Quad</u>	<u>Move</u>	
E12	.150"	downward
E36	.090"	} upward
F13	.073"	
F45	.049"	
Predicted rms	.081	
Predicted max	.226	at C45

The corrected orbit is given by the dashed curve in Fig. 5. By including a move at D49F the correction can be made exclusively to E and F sectors, but placement errors would probably disturb the rest of the ring nearly as much as predicted for the four-magnet move. The predicted change of about $1/16''$ at the Lambertson septum seems acceptable. Although the bump in C-sector would be amenable to the same treatment it seems desirable to see the results of the suggested moves to permit an easier interpretation of the results.

It has been observed that the difference of closed orbit measurements can point quite clearly to magnets which deteriorate between the measurements. For this reason it seems advisable to retain a few generations of measurement on the PDP-10 disk for comparison. Also, for this reason measurements should be taken as often as practical, not just after quadrupoles have been moved. We have not yet sufficient experience to know what the long-term stability of the closed orbit is. If there are day-to-day changes the effort made to reduce distortions below the order of such changes is wasted.

It is important to note that the closed-orbit correction obtained by moving quadrupoles is dependent on knowing the tune of the machine. As the tune approaches an integer value, for instance, any particle arrives at a given quad with nearly the same phase over several turns so that a small displacement produces a large orbit distortion. Since the technique employed does not correct the geometry of the ring to nominal but rather introduces compensatory distortions, the correction will be good for only the ν value for which it was calculated. The larger the individual magnet moves have been (and ours have been quite substantial) the more sensitive the closed orbit is to ν change.

Table I: Main Ring Closed Orbit

<u>Date</u>	<u>Horizontal</u>			<u>Vertical</u>			<u>Energy</u>		
	<u>rms</u>	<u>Max</u>	<u>Location</u>	<u>v_x</u>	<u>rms</u>	<u>Max</u>		<u>Location</u>	<u>v_y</u>
3/10	.478	1.29	C36	x	.227	.600	D39	x	70
4/12	x	1.25	A42	x	x	.95	D39	x	80
4/14	.548	1.12	E42	20.42	.162	.486	D39	20.3	80
5/7	x	1.8	C42	x	x	.25	C37	x	140
5/19	x	.8	F32	x	x	.3	C37	x	80
5/28	.287	.759	E19	20.42	.154	.341	E49	20.3	70
7/9	.284	.773	A42	20.28	.117	.364	F12	20.2	90

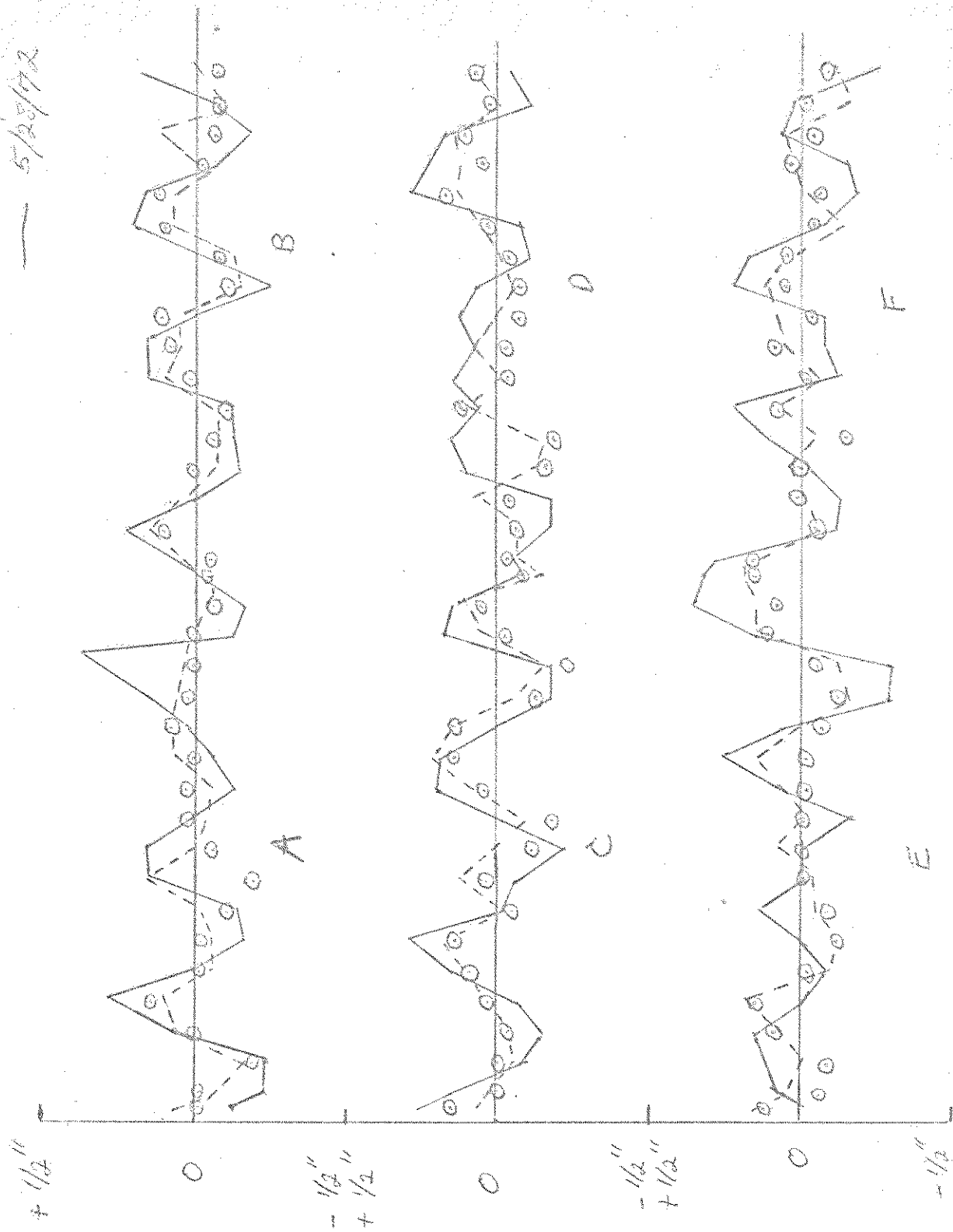
Table II: Quadrupole Moves

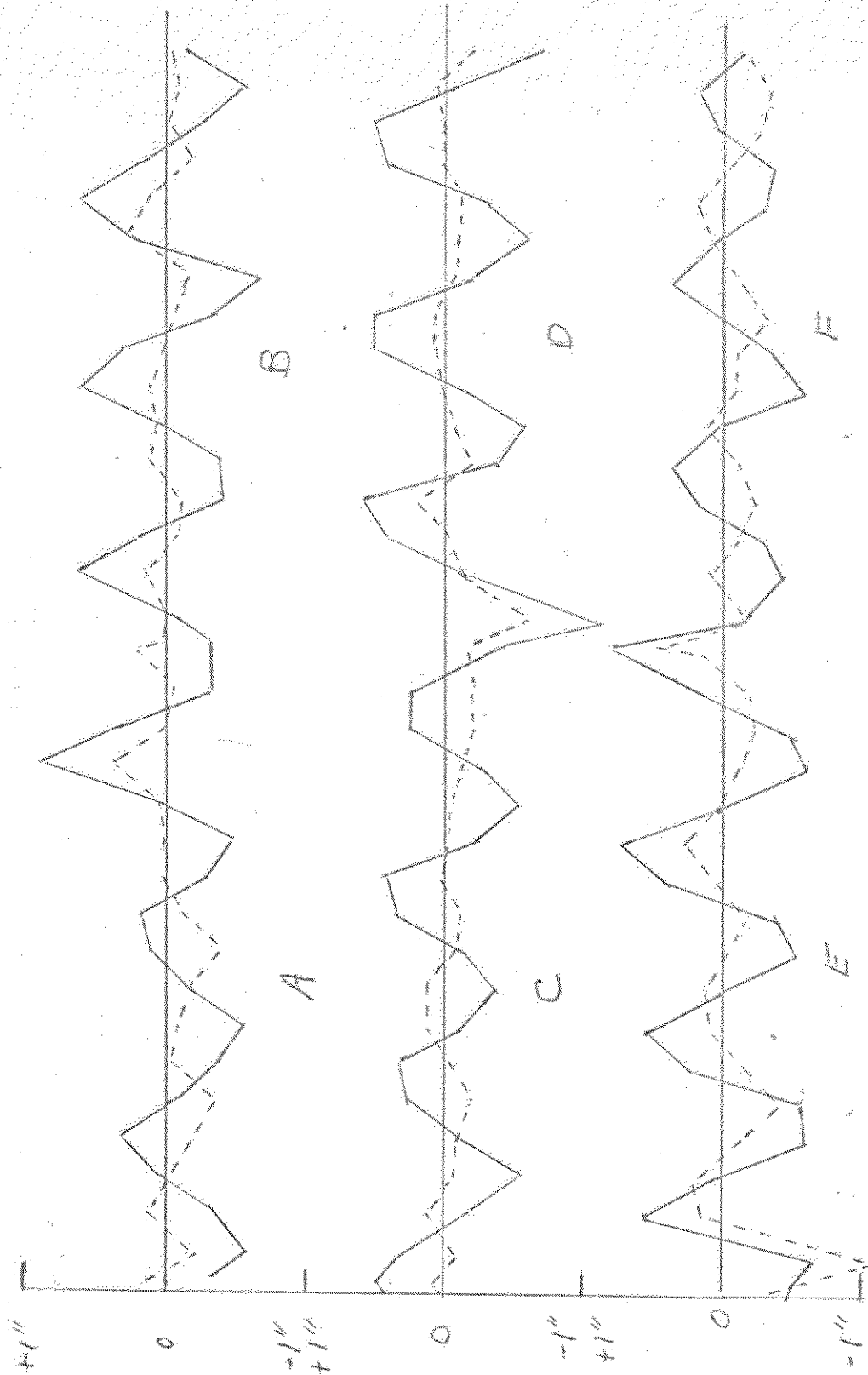
<u>Date</u>		<u>Predictions</u>					
		<u>Horizontal</u>			<u>Vertical</u>		
		<u>rms</u>	<u>Max</u>	<u>Location</u>	<u>rms</u>	<u>Max</u>	<u>Location</u>
4/13	C25, F25	x	x	x	.174	.525	D39
5/2	A18, A43, D23 D47, F43, F45	x	x	x	.090	.238	C45
5/12	All doublets A13, E34	.200	.462	A46	x	x	x
7/*	H: A15, A32, B16 D43, F23	.180	.547	E11			
	V: E12, E36, F13, F45	x	x	x	.081	.226	C45

*Suggested moves

VERTICAL CLOSED ORBIT

○ Calculated
 --- 5/17/72
 — 5/23/72

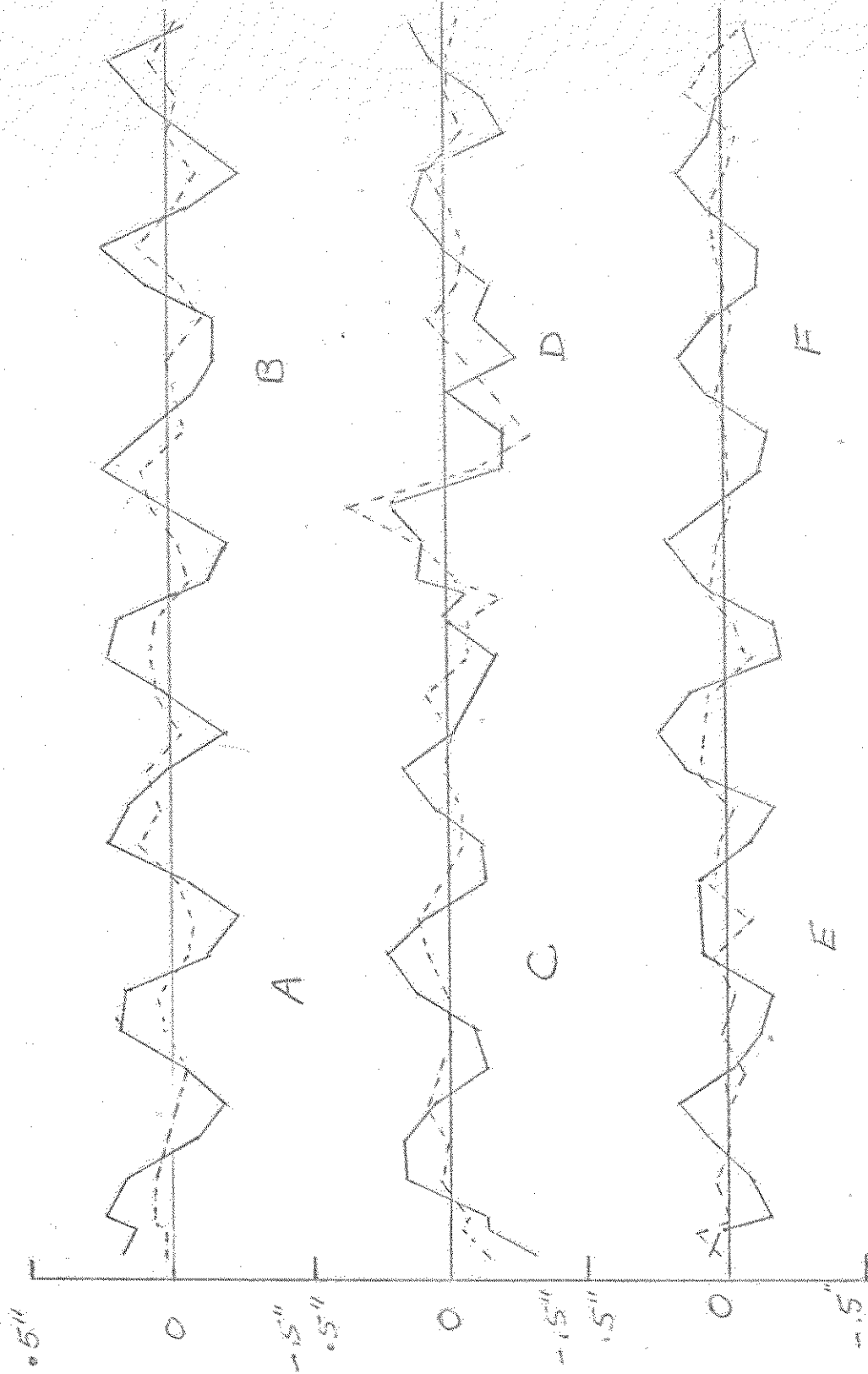




HORIZONTAL CLOSED ORBIT DIFFERENCE (DATA 7/4 - DATA 5/28)

— DIFFERENCE ORBIT
 - - - CORRECTED BY δ_{HIP}

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VERTICAL CLOSED ORBIT DIFFERENCE (DATA 7/9 - DATA 5/28)

— CLOSED ORBIT DIFFERENCE
 - - - - - CORRECTED BY $S_{AID} = -1.045$

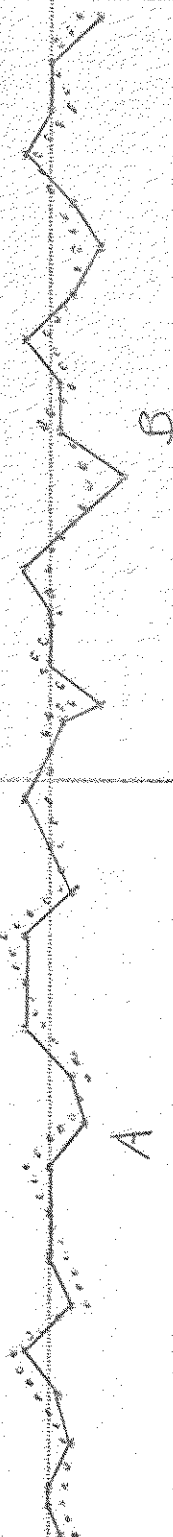


Quad Moves: $b_{415} = -.114$ $b_{543} = .062$
 $b_{491} = .085$ $b_{523} = .132$
 --- measured --- Predicted Correlation

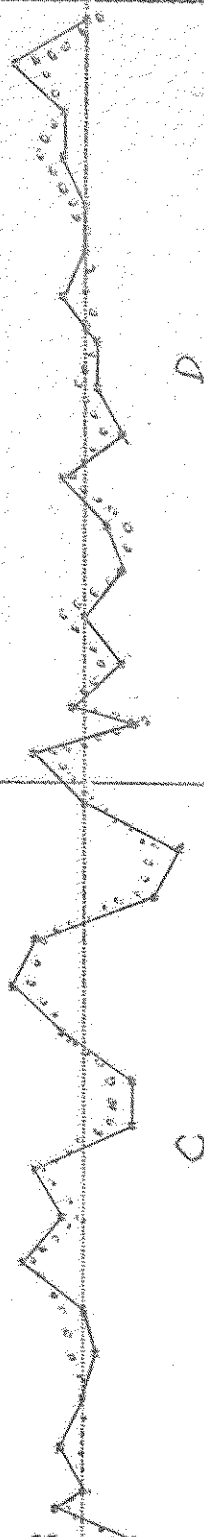
VERTICAL CLOSED ORBIT (DATA 7/9/72)

AT IT # 1 RUNS 8.11E-02 MAX= 2.22E-01 AT 045

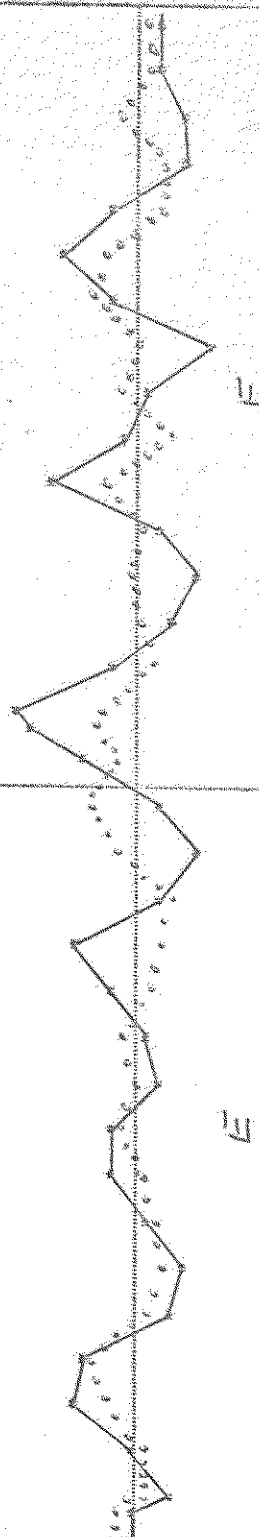
F43



B43



D43



STATION "NUMBERS" →

21 33 43

QUAD MOVES: $\delta_{E12} = -1.50$ $\delta_{E13} = .073$

$\delta_{E36} = .090$ $\delta_{E45} = .049$

MEASURED 7/9/72
... PREDICTED
CORRECTION

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